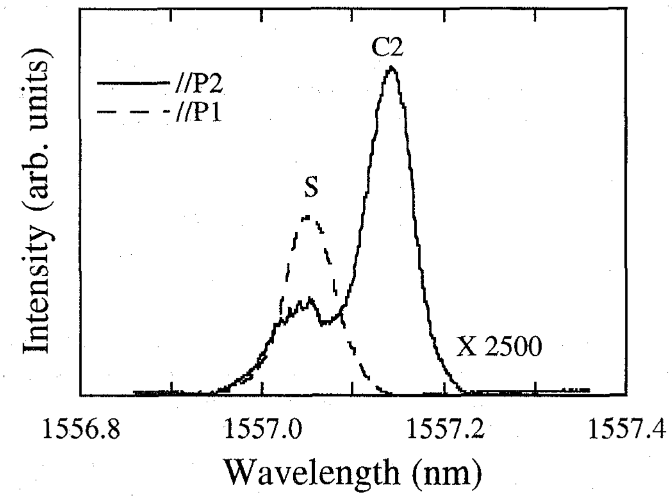

WB6 Fig. 2. Conjugate and suppressed signal at the output of a converter made using a 0.5-mm amplifier, after a polarizer suppressing the polarization parallel to P1. P1-S detuning is $\Delta f = 120$ GHz. Dashed line is the component of the signal parallel to P1, hence orthogonal to C2, demagnified 2500 times.

the same frequency is thereby possible. The frequency of C2 is tuned by tuning the frequency of P1 and P2, with fixed Δf. Because FWM efficiency is expected to be almost independent of P1-P2 detuning, the frequency conversion efficiency is virtually flat. A high efficiency is obtained because the frequency of S is lower than that of P1 for either up- or down-conversion of the signal. Assuming the optimal case of equal output pump intensities, efficiency and SNR are 6 dB less than the single pump scheme for the same saturated gain and the same Δf, independently of the P2 polarization. The polarizer at the SOA output also suppresses the amplified spontaneous emission noise generated by the in-line amplifiers downstream and amplified in the SOA. Our converter can be made polarization independent by a polarization diversity scheme in which two orthogonal components of the signal polarization are independently converted.

Preliminary measurements with a 0.5-mm-long polarization-insensitive Opto Speed bulk amplifier show FWM efficiency virtually independent of the conversion range for fixed Δf. The intensity of S was suppressed by the polarizer 5 dB below the intensity of C2 (see Fig. 2). With 2-mm-long amplifiers, the conversion efficiency is expected to increase by approximately 20 dB, the saturated gain by only 5 dB.[1] Suppression of S more than 15 dB below C2 is therefore attainable. Results on longer amplifiers will be presented at the conference.

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1. A. D'Ottavi, F. Girardin, L. Graziani, F. Martelli, P. Spano, A. Mecozzi, S. Scotti, R. Dall'Ara, J. Eckner, G. Guekos, IEEE J. Sel. Top. Quantum Electron. **3**, 522–528 (1997).
2. A. D'Ottavi, E. Iannone, A. Mecozzi, S. Scotti, P. Spano, R. Dall'Ara, J. Eckner, G. Guekos, Appl. Phys. Lett. **65**, 2633–2635 (1994).
3. J. Zhou and K. Vahala, in *Conference on Lasers and Electro-Optics*, Vol. 15 of 1995 OSA Technical Digest Series, (Optical Society of America, Washington, D.C., 1995), p. 367.

WB7 **10:00am**

30-nm wavelength conversion at 10 Gbit/s by four-wave mixing in a semiconductor optical amplifier

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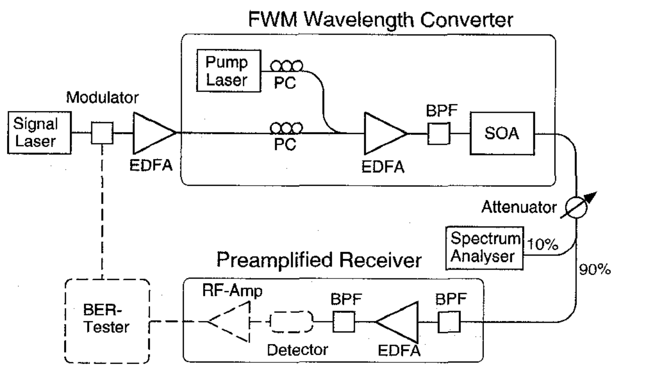
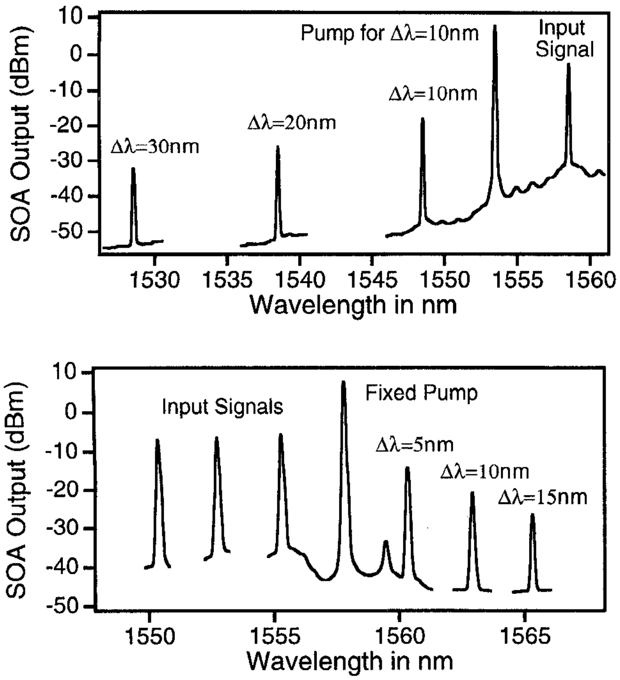
Four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is currently the only available strictly transparent wavelength-conversion technique, which is not penalized by phase matching.[1] The span of the conversion is limited primarily by conversion efficiency and signal-to-noise (SNR) issues,[1] both of which are expected to improve with the use of longer SOAs.[2] In this paper, we demonstrate significantly enhanced performance of long converters in a system experiment at 10 Gbit/s. The experiment shows for the first time, to our knowledge, that FWM wavelength down-conversions can span the full gain bandwidth of erbium-doped fiber amplifiers (EDFAs).

The experiment is schematically shown in Fig. 1 and is similar to that described in Ref. 1. The SOA was a 1.5-mm-long bulk active layer structure, temperature controlled and biased at 670 mA. The maximum small signal fiber-to-fiber gain of the amplifier was 24 dB at 1565 nm (limited by amplified spontaneous emission (ASE) gain saturation), and the total optical power coupled into the device was +15 dBm. To reduce the ASE noise from the high-power EDFA (located before the SOA) in the converted signal band, the input signal and the pump were also passed through a broad bandpass filter at the SOA input (15-nm bandwidth). The power ratio of the pump to the probe was about 10 dB (measured at the SOA output), a value which was found to minimize errors due to cross-gain modulation of the pump by the probe, while maintaining good conversion performance.

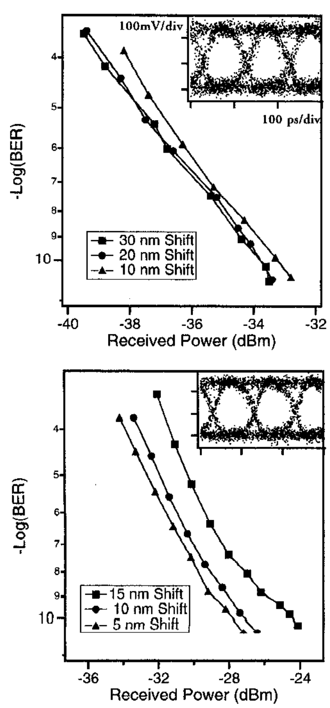
The SOA output spectrum for three different up- and down-conversions is shown in Fig. 2. For the down-conversion, the input signal was fixed at 1558 nm and the pump was tuned to achieve the desired shifts. Conversely, in the up-conversion, the pump was fixed at 1558 nm and the signal wavelength was tuned. This configuration was chosen to take full advantage of the spectral dependence of the SOA gain. The span of the 10 Gbit/s down-conversion was limited by the width of the 15 nm ASE prefilter, while for the up-conversion the limit was set by converted signal-to-ASE noise ratio.



WB7 Fig. 1. Schematic of the experimental setup. PC: polarization controller; EDFA: erbium-doped fiber amplifier; BPF: bandpass filter (all 1-nm bandwidth, except the one just before the SOA); SOA: semiconductor optical amplifier; BER: bit error rate. Dashed lines carry electrical (RF) signals.



WB7 Fig. 2. Spectra measured at the output of the SOA (0.1-nm resolution bandwidth). The upper shows the down-converted signals for the 30-, 20-, and 10-nm shifts (from left to right). For the smallest shift, we also show the pump and the input signal. The pump wavelength was tuned to lower wavelengths at constant power to achieve the larger shifts. The lower figure shows the up-converted signals for the 5-, 10-, and 15-nm shifts (from right to left). In this case, we changed the input signal wavelength and the pump remained the same for all three shifts. The small peak near 1559.5 nm is a distributed feedback sidemode.



WB7 Fig. 3. BER vs. received signal power for the shifts in Fig. 2. The received signal power was measured at the 10% tap after the attenuator with 0.2-nm resolution bandwidth. The eye diagram in the inset corresponds to the largest shift in each case, with no attenuation.

Figure 3 shows the bit error rates (BER) versus converted signal power measured at the output of the 10% bi-directional coupler in Fig. 1. There is almost no additional penalty when going from 10 to 30 nm shifts in the down-conversion, while for the up-conversion there is a 3 dB penalty going from 5 to 15 nm of up-shift. These record conversions are primarily attributed to the long length of the SOA. Further improvements are expected going to even longer devices. The lower up-conversion performance stems from the well-known detuning asymmetry in the FWM nonlinearity,[1] as well as from the SOA and receiver EDFA gain spectrum.

In conclusion, we have demonstrated a record 30 nm of wavelength down-shifts and 15 nm of up-shift for 10-Gbit/s optical signals. The improvements result from the use of long (1.5 mm) SOAs. Further improvements in performance are anticipated with yet longer devices.

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1. D.F. Geraghty, R.B. Lee, K.J. Vahala, M. Verdiell, M. Ziari, A. Mathur, IEEE Photon. Technol. Lett. **9**, 452–454 (1997).
2. F. Girardin, J. Eckner, G. Guekos, R. Dall'Ara, A. Mecozzi, A. D'Ottavi, F. Martelli, S. Scotti, P. Spano, IEEE Photon. Technol. Lett. **9**, 746–748 (1997).

WB8 10:15am

Wavelength conversion by four-wave mixing in a folded-path, self-pumped semiconductor optical amplifier

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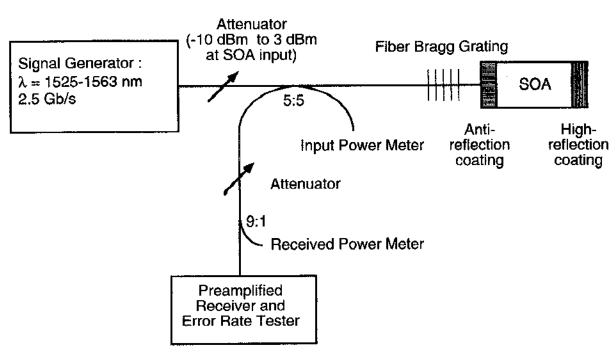
Wavelength conversion is recognized as a key function for the implementation of complex wavelength-division multiplexing (WDM) communication systems. Of the approaches demonstrated so far, only four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is fully transparent to modulation format and bit rate while providing arbitrary wavelength mapping. Recent demonstrations[1,2] have shown that the performance of FWM converters can be made technologically competitive. Here we present a novel wavelength conversion scheme that offers additional advantages while significantly reducing the complexity of the device.

The converter consists of an external-cavity semiconductor laser, with a high-reflection coating on one facet, and a fiber Bragg grating pigtailed to the other facet (anti-reflection coated). The pump wave is



WB8 Fig. 1. Schematics of the experimental setup.